Toxic Release Route Index for Inherently Safer Plant Design

By

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Dissertation submitted in partial fulfilment of
The requirement for the Bachelor of Engineering (Hons)
(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved by,

_____

Dr Dzulkarnain Zaini

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained here have not been undertaken or done by unspecified sources or person.

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SHAMIL BIN ASARI

ABSTRACT

An inherently safer design is one that avoids hazards instead of controlling them, particularly by reducing the amount of hazardous material and the number of hazardous operations in the plant. Methods developed to date have largely been for the evaluating the safety of a proposed design. In the future the emphasis will be more and more on the synthesis of an inherently safer plant.

In conceptual design, process routes can be compared and ranked by using inherent safety indices. In this project, an index will be developed and are used to evaluate the safest route for toxic release. As a case study, the evaluation of methyl methacrylate process routes is presented. In this case study the results of index methods are compared with expert evaluations of inherent safety level of process routes and the sub-processes included. Also the rankings of process routes given by indices are compared with expert evaluations.

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CONTENTS

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Safety is becoming one of the most crucial aspects in chemical process industry. This is due to several major accidents (such as Bhopal) involving chemical plants that results in thousands of deaths and loss of property. These accidents highlights the importance of planning for emergencies and of designing plants to minimize the occurrence and consequences of spills of toxic, flammable and explosive material.

According to Crowl and Louvar (2002), major accident is defined as “an unexpected, sudden occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving more dangerous substance”. Throughout the year, many new safety procedures introduced to evaluate hazards. However, accidents keep on happening because the available solutions do not minimize or eliminates them (Kletz, 1991).

The Bhopal disaster, India, on 1984 was a perfect example of major accident involving the release of toxic substances. This incident receives considerably more attention compared to others mainly due to more than 2000 civilians causalities recorded. The plant produces methyl iso-cyante (MIC) which is an intermediate product of pesticides. MIC is reactive, toxic and volatile which makes it an extremely dangerous compound. An estimated 25 tons of MIC released and spread to the town nearby, killing over 2000 civilians and injuring over 20000 people. Individuals who in contact with MIC concentration above 21 ppm will experience severe irritation of the nose and throat and could lead to death due to respiratory distress (Crowl and Louvar, 2002).

The study of case history is an important step in the process of accident prevention and improving safety procedure to prevent similar accidents in the future. These major accidents had a significant impact to the chemical engineers profession in the implementation of new standard for the safety practice.

1.2 Problem Statement

Over the years, there are many methods have been practiced in the chemical processing plant in order to analyze the hazards. The examples of method usually used are DOW Fire and Explosion Index (DOW FEI), Hazard and Operability Studies (HAZOP), Quantitative Risk Assessment (QRA), et cetera. These, typical approach of loss and prevention and safety measures are considered at the end of the design process, leaving add-on control measure to be the only option available (Khan & Amyotte, 2005). The protective measure which added late in the design process requires regular preventive maintenance and lead to increase in the operating costs of the plant as well.

The other option to this "traditional safety" approach is to implement inherent safety concept. An inherently safe design (ISD) plant uses chemistry and physics to prevent accidents. Inherent safety aims to reduce or eliminate the source of hazards by altering the design (hardware, controls, operating conditions) of the process plant instead of relying on additional engineered safety system.

Many previous studies on inherent safety level (ISL) quantification index based are focusing on processing route. However, most of the work for index based ISD approach focusing on chemical route by using properties of single component. These indices lack of considering the chemical component as a mixture and developed purposely for toxic release.

After determining the safest route, the ISD can be applied at this stage by improving the inherent safety level of the streams. Further improvement can be done to ensure the ISD by ranking the process streams based on ISL within a process route. The selection of most hazardous streams can be done if the ISL of the process streams can be ranked through the technique such as the index based ISD approach. However, this concept has never been used for toxic release of the process streams.

1.3 Objectives and Scope of Study

The main objectives of the project are:

1. To develop an inherently safer design technique for process plant using process route index for toxic release method, Toxic Release Route Index (TRRI).

2. To apply developed technique on case study to demonstrate its application and usefulness.

Scope of Study

This project developed a prototype to perform the tasks of process route screening, process stream prioritization and inherent risk assessment for inherent safety level quantification (ISL) of toxic release. The first task in to screen the process route using an overall index based on their potential to produce major hazards. In the second task, design engineers can further evaluate the inherent hazards. This index ranks the process streams within the process route relatively to identify and prioritize the streams.

This work is incorporated into a prototype computer software tool based on a Microsoft Excel spreadsheet via Visual Basic for Application (VBA) language to capitalize its calculation capability and also its ability to communicate with the process design simulator (PDS), i.e. HYSIS and iCON.

However, human intervention is still required for making decisions and to proceed with additional improvement or modifications. In addition, it is important to note that irrespective of the modifications carried out to enhance the level of inherent safety should not in any way harm the original design intent and product specifications.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Major accidents involving chemical processing plant cause a huge loss to life, property, livelihood and environment. Hazardous material can lead to many forms of accidents such as serious fire, explosion or toxic release. Toxic release is one of the main hazard in processing plant that have caused many fatal accident, although the accidents in which greater lost of life and damage occur are caused by explosion (Chan, 2004). Thus, risk assessment and safety aspect of process plant should be given more attention and have been further intensified after Flixborough and Bhopal accidents.

2.2 Hazard Analysis

Many guidelines and procedure has been introduces especially for the past three decades with respect to risk assessment and safety of chemical plants. Some of the few conventional methods that have been practised in the industry are:

2.2.1 Hazard and Operability Studies (HAZOP)

HAZOP were initially invented by Imperial Chemical Industries (ICI) in the United Kingdom, but the technique only widely used within the chemical process industry after the Flixborough disaster in which a chemical plant explosion killed 28 people, many of which were ordinary householders living nearby. Through the general exchange of ideas and personnel, the system was then adopted by the petroleum industry, which has a similar potential for major disasters.

According to Crowl and Louvar (2002), the basic idea of HAZOP studies are they work by using the imagination of members of a team to visualize the ways in which a plant can malfunction or be mal-operated. HAZOP studies require members composed of a cross section experienced plant, laboratory, technical and safety professionals. The studies are carried out in a team and hence the quality of study is highly dependent on experience and open influence of team members.

HAZOP is based on guide words such as no, more, less, reverse, other than, which should be asked for every pipe and vessel. The intention of the guide words is to stimulate the imagination, and the method relies very much on the expertise of the persons performing the analysis. The idea behind the questions is that any disturbance in a chemical plant can be described in terms of physical state variables. The sample of HAZOP worksheet is attached in the appendix section.

2.2.2 DOW Fire and Explosion Index (DOW FEI)

The DOW FEI is a ranking system that produces a relative index to the risk of individual process units due to potential fires and explosions. It was developed by DOW Chemical Company back in 1964 and later shared and practiced with the industry. The DOW FEI method starts by identifying and dividing the process into separate process units. The purpose of the DOW FEI is to:

- Quantify the expected damage of potential fire and explosion incidents in realistic terms,
- Identify equipment that would be likely to contribute to the creation or escalation of an incident and
- Communicate the fire and explosion risk potential to management. The Dow Index is the product of the Unit Hazard Factor and the Material Factor.

The material factor (MF) is selected from a predefined table. The hazards arising from process conditions are characterized by two factors, which is General Hazard Process Factor (F_1) and the Special Process Hazard Factor (F_2). Fire & Explosion Index (F&EI) is obtained by using the equation 2.1. Table 2.1 shows the level of DOW Fire and Explosion Index.

$$F\&EI = F_1 \times F_2 \times MF \qquad \textbf{Eq. 2.1}$$

Table 2.1: Level of hazard and DOW Fire and Explosion Index

DOW F&EI	Degree Of Hazard
1 – 60	Light
61 – 96	Moderate
97 – 127	Intermediate
128 – 158	Heavy
159 and above	Severe

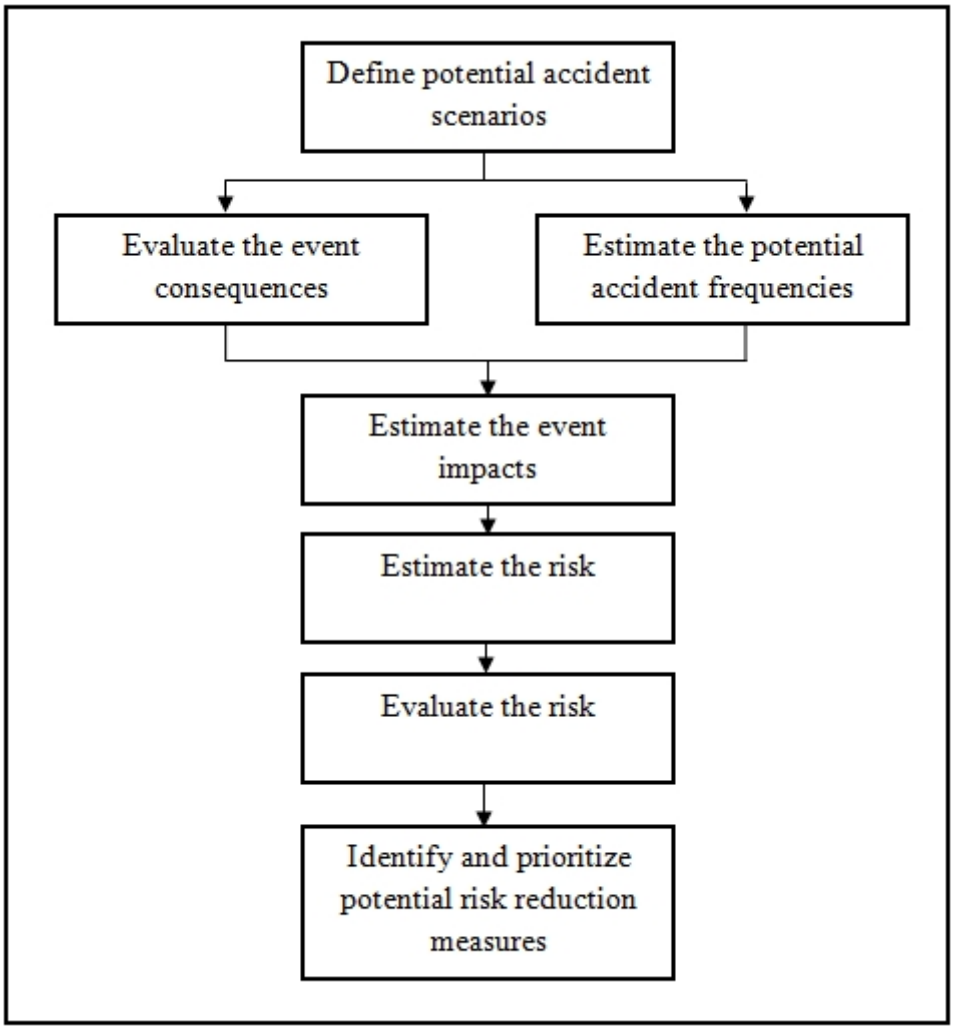
2.2.3 Quantitative Risk Assessment (QRA)

QRA is a method that identifies where operations, engineering, or management systems can be defined to reduce risks (Crowl and Louvar, 2002). The complexity of QRA depends on the objectives of the study and the available information. The Centre of Chemical Process Safety (CCPS, 2000) defines risk as a measure of human injury, environmental damage or economic loss in term of both the incident likelihood and the magnitude of the loss or injury. Wentz (2009) once proposed risk as a mathematical function which shown in equation 2.2 below:

$$Risk = f(probability\ or\ frequency, consequences) \qquad \textbf{Eq. 2.2}$$

The extent of the risks and the effects of risk reducing measures can successfully be done by using QRA as illustrated in figure below:

Figure 2.1: Quantitative Risk Analysis Flowchart (CCPS, 1999)



2.3 Inherent Safety

Inherent safety (IS) is a proactive approach for hazard or risk management during process plant design and operation. Inherently safer technology (IST) permanently eliminates and reduces hazards in order to avoid or reduce the consequences of incidents, rather than using add-ons protection measures to control the risks arising from hazards.

Professor Kletz (1998), was the first to formalize the principle of inherent safety. Table 2.2 below shows the commonly used inherent safety principles or guidewords.

Table 2.2: Inherent Safety Principles

Inherent safety principle	Definition
Intensification	Reduction in the quantity of hazardous materials
Substitution	Use of safer materials
Attenuation	Operation at comparably safer operating condition such as room temperature and pressure
Limitation of effects	Changing the design and operation for less severe effects
Simplification	Avoidance of complexity such as multi-product operations or congested pipe setting
Error of tolerance	Making equipment robust, processes that can bear upsets, reactor able to withstand unwanted reactions
Avoiding knock-on effects	Ample layout spacing, fail-safe shutdown, open construction
Making status clear	Avoidance of complicated equipment and information overloading
Ease of control	Less hands-on control
Making incorrect assembly impossible	Unique valve or piping system to reduce human error

Major decisions on process principles are done in the process development and conceptual design phases. Therefore the preliminary design phases give the best opportunities of implementing the inherent safety principles. In fact the possibility of implementing inherent safety decreases as the design proceeds. Thus, the inherent safety characteristics should be evaluated systematically as early as possible. However, analysis has shown that IS does not end at invention phase. The ideal inherently safer process and engineering design culture can be developed at any stage of the process. The largest payoffs are achieved by verifying IS principles have been considered early in the engineering design process.

2.4 Previous Methodologies for Quantification of Inherent Safety Level (ISL)

Previously, there have been many methods in quantification of inherent safety level introduced by a number of researchers.. Information requirements of the methods are different and also the results produced may vary. Thus different safety methods are suitable for different stages of process development, design and operation. The fundamental concept of quantification of inherent safety level was based on the ranking of chemical process routes.

The first index published for evaluating the inherent safety in was the Prototype Index for Inherent Safety (PIIS) by Edwards and Lawrence (1993). Basically, the indices for ranking alternatives chemical routes by Lawrence incorporated seven parameters relates to the physical properties of the chemicals and conditions of reaction steps which are, the temperature, pressure, reaction yield, inventory, toxicity, explosiveness and flammability. For each of these parameters, a table of scoring parameters was developed. The case study that has been used to implement the prototype index was tested by using a number of routes to produce Methyl Methacrylate (MMA). Since it is a pioneering work, the rankings of process routes given by indices are compared with expert evaluations that ranks alternative route independently. The experts opinion are assumed to be worthy of consideration and the results shows that the ranking by these experts are close to the prototype index calculations.

Besides, Inherent Safety Index (ISI) by Heikkila (1999) was also one of the early researchers to propose indices that are function of pressure, temperature, composition, et cetera. As shown in table 2.3 and 2.4, ISI consists of two main index groups. The chemical inherent safety index describes the chemical aspects of inherent safety, and the process inherent safety index represents the process related aspects. These set of parameter contains thirteen parameters which is almost double the number of parameter proposed by Lawrence. Most of the sub-indices of the method can be estimated quite easily by using physical or chemical properties of compounds present, or based on operating conditions and a concept of the process. There is also one sub-index that allows an experience-based evaluation of the safety of the process structure.

Table 2.3: Chemical Inherent safety sub-indices (ISI)

Chemical inherent safety index	Score
Heat of main reaction	0 to 4
Heat of side reaction, max	0 to 4
Flammability	0 to 4
Explosiveness	0 to 4
toxicity	0 to 6
Corrosiveness	0 to 2
Chemical Interaction	0 to 4

Table 2.4: Process Inherent safety sub-indices (ISI)

Process Inherent safety index	Score
Inventory	0 to 5
Process temperature	0 to 4
Process pressure	0 to 4
Equipment safety - (Inside Battery Limits)	0 to 4
Equipment safety - (Outside Battery Limits)	0 to 3
Safety of process structure	0 to 5

The following researchers focused to improve the indices such as i-Safe by Palaniappan (2002). The i-Safe Index developed by Palaniappan (2002 and 2004) compares process routes by using sub-index values taken from ISI and PIIS. In addition, it includes a NFPA reactivity rating values for the chemicals present.

For the individual reaction steps the Overall Safety Index (OSI) includes Individual Chemical Index (ICI), and Individual Reaction Index (IRI). Meanwhile, the indices for the whole process are, Hazardous Chemical Index (HCI), Hazardous Reaction Index (HRI), Overall Chemical Index (OCI), Overall Reaction Index (ORI), Overall Safety Index OSI, Worst Chemical Index (WCI), Worst Reaction Index (WRI) and Total Chemical Index (TCI).

Individual Chemical Index ICI is determined by the properties of the chemicals involved in the reaction, and it is calculated as a summation of indices assigned for flammability (N_f), toxicity (N_t), explosiveness (N_e) and NFPA reactivity rating (N_r). In ICI, all subindex values come from ISI, except the reactivity rating, which comes from NFPA reactivity rating values for chemicals.

Individual Reaction Index IRI is calculated as a summation of subindices for temperature (R_t), pressure (R_p), yield (R_y) and heat of reaction (R_h), which is quite

similar to the process score for PIIS except that the heat of reaction is added. The index values, however, are taken from ISI, except the yield, which comes from PIIS.

Table below shows how the calculation of the i-Safe index.

Table 2.5: i-Safe index calculations

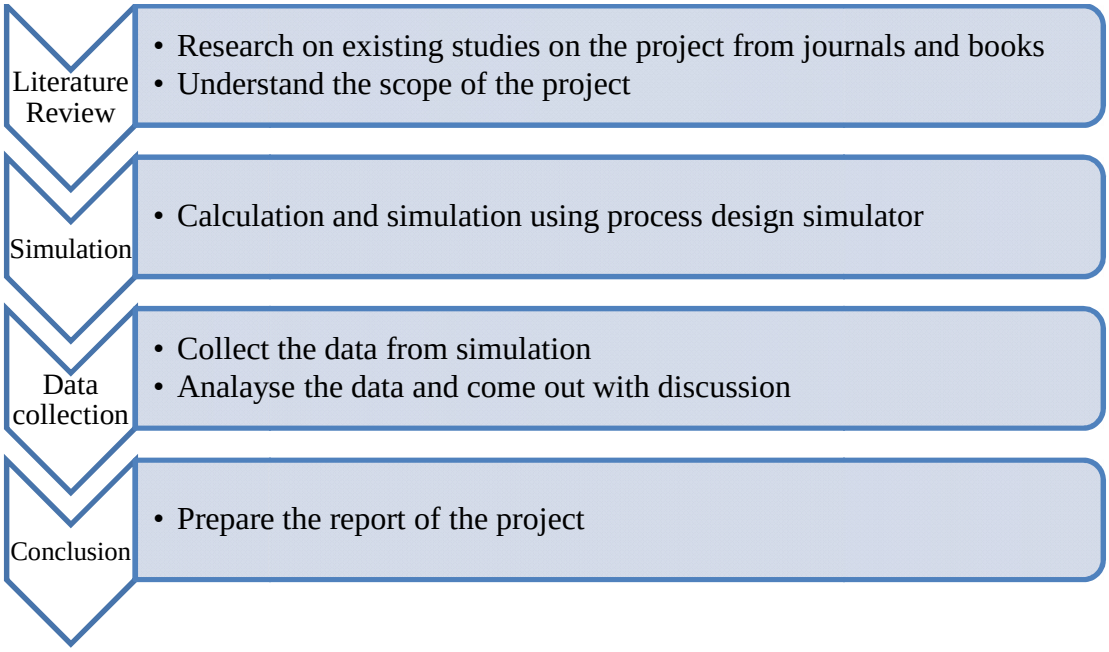
Component of inherent safety index	Notation	Equations
Individual chemical index	ICI	$N_r + N_f + N_t + N_e$
Individual reaction index	IRI	$R_t + R_p + R_y + R_h$
Hazardous chemical index	HCI	max(ICI)
Hazardous reaction index	HRI	max(IRI)
Overall chemical index	OCI	max(ICI)
Overall reaction index	ORI	∑IRI
Overall safety index	OSI	∑(OCI + ORI)
Worst chemical index	WCI	$\max(N_r) + \max(N_f) + \max(N_t) + \max(N_e)$
Worst reaction index	WRI	$\max(R_t) + \max(R_p) + \max(R_y) + \max(R_h)$
Total chemical index	TCI	∑ICI

CHAPTER 3: METHODOLOGY

3.1 Project Flowchart

This project proposed and demonstrated an evolution of concept to quantify risk, which is inherent to the process plant at preliminary design stage. It is carried out by using an inherent risk assessment which is integrated with process design simulator to allow data transfer. A case study will be used to illustrate the advantage of implementing this technique. Below is the overview of the workflow of the project.

Figure 3.1: General Project Flowchart



3.2 Project Gantt chart

Table 3.1: Project Gantt Chart FYP I

No	Detail Work	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of project topic														
2	Preliminary reseach work														
3	Preparation of extended proposal defence														
4	Submission of extended proposal defence														
5	Proposal defence														
6	Project work continues														
7	Submission of interim draft report														
8	Submission of interim report														

Table 3.2: Project Gantt Chart FYP II

No	Detail Work	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Identify the process route														
2	Identify the chemical and the physiochemical characteristics														
3	Calculation of toxicity level														
4	Calculation of toxic release route index (TRRI)														
5	Rank the route according to TRRI														
8	Preparation of poster, technical report and dissertation														
9	Pre-SEDEX														
10	SEDEX														
11	Submission of technical paper														
12	Oral Presentation														

3.3 Toxic Release Route Index Methodology

Different index methods evaluate the processes by using a different set of criteria. These criteria are measured by the sub-indices used in the methods. Considering the differences in criteria will also helps us to understand the differences between the results of indices. Practically, the development of indices is difficult. The relative importance of each parameter that contributes to the indices is subjective and relying on the analyst's experience and technique. Thus the indices methodology can be as rudimentary and sophisticated as necessary to fulfil the needs of a study, depending on analyst's discretion and not fixed by law (CCPS, 1996).

CCPS (1996) recommends that the indices methodology needs to factor in the chemical and physical properties as well as conditions. Numerical indices should also be based upon known theoretical relationship or empirical correlation among parameters. For example Lawrence (1996) proposed a four parameters structure in his doctoral thesis which is shown below:

Inventory * Hazard Assessment * Probability of Release * Effects Modifier

The above asterisk (*), means that parameters are 'combined in some way' and not necessarily by multiplication. These combining parameters will depend upon how the parameters are structured, for instance if they are all scores then addition is the most appropriate, while if inventory is in 'ton' and hazard assessment is in 'hazard per ton' then multiplication is the most reasonable way.

Toxic Release Route Index (TRRI) is a representative numerical to present the ISL of process route by using an overall index based on the average value of the parameters that influence the consequence by using combined effect of parameters. In TRRI case the parameters is the combined effect of the mass release and toxicity level (TL). With reference to the equation 3.1 shown next, for the mass release, the simplest assumption is that a sudden loss of containment accident from a stream or pipeline in a process route will release a mixture of airborne chemicals over a short period of time (Calamari and Vingi, 1993).

$$\langle C\rangle(x,y,z,t) = \frac{G^*}{(2\pi)^{3/2}\,\sigma_x\sigma_y\sigma_z} exp\left\{-\frac{1}{2}\left[\left(\frac{x-ut}{\sigma_x}\right)^2 + \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right]\right\} \quad \textbf{Eq 3.1}$$

Where

C is the time average concentration of centre puff cloud (mass/volume)

*G** is the total mass of material released (mass)

$\sigma_x\sigma_y\sigma_z$ are dispersion coefficient in the x, y, and z directions (length)

x is the downwind direction (length)

y is the crosswind direction (length)

z is the distance above the ground (length)

t is the time since the release of puff cloud (time)

The mass of material release is assumed to be calculated at the instance the rupture occurs, which is a partial release. The toxicity level of mass release also needs to be considered in the determination of toxic release hazard by the chemical substance presence and the effects of each chemical in each route. Following this principle, the TRRI equation is a function of mass release and toxicity level (TL) as further described in equation 3.5.

$$TRRI = f(mass\ release, TL) \qquad \textbf{Eq 3.2}$$

The basis of toxicity level posed by a process plant's route is considered by the chemical components present and the effects of each chemical in the route and stream (Hassim and Edwards, 2006). Practically, the presence of a chemical component in the process route is rarely confined to a single chemical but rather to a mixture. The chemical may be hazardous as a mixture even if the individual components are at concentration below their acceptable toxicity limits. The contributions of combined parameters and the presence of a mixture of chemical components in a stream in the process route can be illustrated as shown in equation 3.3

$$mass\ flow_{avg} = \sum_i (mass\ flow\ in\ stream) \times (mass\ fraction_i) \quad \textbf{Eq. 3.3}$$

The unit for mass flow in stream is kg/s and unitless for mass fraction. In the previous equation, the partial hazard level for an individual chemical, i in each stream is calculated based on its mass fraction in the stream. The total of partial mass flow for chemical in the stream equals the average mass flow for the stream, mass flow avg.

For the purpose of determining the effect of chemical, the National Fire and Protection Agency (NPFA) 704 ranking value in term of its inherent hazard material properties has been chosen. NPFA 04 is a standard system for identification of the hazard material for emergency response (NPFA 704, 2012). The NPFA 704 assigns a value ranging from 1 to 4 to the chemical according to the ability to cause a health hazard. Table 3.2 shows the criteria used to determine the NPFA value for the health hazard. The reason for choosing this standard is to assess the inherent hazards by their ability to cause death or major residual injury to humans (Hassim and Edwards, 2006).

Table 3.3: Standard System for the Identification of the Hazard Material for Emergency Response (NPFA 704, 2012)

	Standard System for the Identification of the Hazard Material for Emergency Response (NPFA 704)
0	Poses no health hazard, no precaution necessary (e.g. water)
1	Exposure would cause irritation with only minor residual injury (e.g. acetone)
2	Intense and continued but no chronic exposure could cause temporary incapacitation or possible residual injury (e.g. ethyl ether)
3	Short exposure could cause serious temporary or moderate residual injury (e.g. chlorine gas)
4	Very short exposure could cause death or major residual injury (e.g. hydrogencynade, phosphine, carbon monoxide)

Besides using NPFA 704 to determine the toxicity level, another possible way to evaluate the toxic exposure is based on the Threshold Limit Values (TLV) because TLV data is readily available for most substances in process industry. TLV values express the harmful exposure limits of substances in the threshold time of 8 hours. The index value is higher when the TLV is lower which means the substance is more toxic. It is important to use TLVs with same threshold time so that the results are comparable. The value of TLV can easily be obtained in MSDS of the component in the appendix.

Table 3.4: Toxic limit and score

Toxic limit (ppm)	Score
TLV > 10000	0
TLV < 10000	1
TLV < 1000	2
TLV < 100	3
TLV < 10	4
TLV < 1	5
TLV < 0.1	6

Theoretically, the toxicity is a function of mass flowrate and the effect of the chemical.

$$toxicity\ level\ (TL) = f\left(mass\ flow_{avg}, NPFA\ 704\ or\ TLV\ score\right) \quad \textbf{Eq. 3.4}$$

Substituting equation 3.3 into equation 3.4 yields equation 3.5

$$TL = \sum_i (mass\ flow\ in\ stream) \times (mass\ fraction) \times (NPFA\ 704_i\ or\ TLV\ score_i) \quad \textbf{Eq. 3.5}$$

In order to allow the transfer of process data from the process design simulator to TRRI, the term mass release in equation 3.2 has to be converted into basic process parameters. By using the principles in fluid mechanics, the amount of mass release through a hole or rupture which is function of density and pressure of the stream could be determined. Substituting density and pressure into equation 3.2 yield equation 3.6:

$$TRRI = f(pressure, density, TL) \quad \textbf{Eq. 3.6}$$

Most of the indices developments are based on arbitrary decision. There is no single method to perform the indices exercise and the analyst can choose to develop their own numerical indices customized to their needs. For example the calculation of the Chemical Exposure Index (CEI) from Dow Chemical Company is a value of dimensionless arbitrarily defined numerical scale even though the parameters that contribute to the CEI are consisted unit measurements (CCPS, 1996). By following this previous indices experience, the TRRI is an arbitrarily average parameters combination calculations that influences the toxic release which is also dimensionless in value. Since the TRRI is to represent the overall process route index, the average value of parameters in equation 3.6 is selected which results in equation 3.7:

$$TRRI = [(average\ density) \times (average\ pressure) \times (average\ TL)] \times A_0$$

Eq. 3.7

All the process parameters in equation 3.7 can be obtained from process design simulator to a Microsoft Excel spreadsheet in tabulated format for indexing calculation. The empirical constant A_0 serves to reduce or increase the magnitude of the resulting numbers in calculation of TRRI and the magnitude is adjusted up to the acceptable level of the end users. In this project, the TRRI is unitless, while for other parameter are kg/m^3 for fluid density, and bar for pressure.

3.4 Methyl Methacrylate process case study

The application of inherent safety indices for this index will be studied by using the manufacturing alternatives for methyl methacrylate (MMA) as a case study. Manufacturing MMA was selected as a case study to allow better comparison of methods, since it was also used by Edwards and Lawrence (1993), Lawrence (1996) and Palaniappan (2002) as an example to demonstrate their indices. The calculations and results for the index will be presented in the next stage of the report which is in Final Year Project 2 report.

CHAPTER 4: RESULTS & DISCUSSION

4.1 Results

Table 4.1: TRRI calculation for Tertiary Butyl Alcohol TBA based route for MMA production

Stream	Contribution of average data to the TRRI						
	Pressure	Density	Toxicity Level				
	bar	kg/m3	Mass Flow	Component	Mass Fraction	TLV Score	TL
CRV 101 top	**4.86**	**1.52**	147.39	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.282	0	0.000
				Tert-Butanol	0.119	2	34.991
				Hydrogen	0.000	0	0.000
				Methacrolein	0.324	2	95.393
				Oxygen	0.000	0	0.000
				M-acrylate	0.276	3	121.953
							252.336
CRV 102 top	**3.50**	**3.02**	165.56	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.035	0	0.000
				Tert-Butanol	0.034	2	11.324
				Hydrogen	0.000	0	0.000
				Methacrolein	0.059	2	19.437
				Oxygen	0.055	0	0.000
				M-acrylate	0.817	3	405.885
							436.646
CRV 102 bottom			0.00	Methanol		2	
				MMethAcryl		2	
				H20		0	
				Tert-Butanol		2	
				Hydrogen		0	
				Methacrolein		2	
				Oxygen		0	
				M-acrylate		3	
							0.000
O2 to CRV 102	350.00	1648.21	100.42	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.003	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.253	0	0.000
				M-acrylate	0.747	3	224.910
							224.910

O2 to CRV 101	4.86	6.07	44.44	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	1.000	0	0.000
				M-acrylate	0.000	3	0.000
							0.000
CRV 103 top	2.00	3.42	85.30	Methanol	0.119	2	20.318
				MMethAcryl	0.471	2	80.282
				H20	0.111	0	0.000
				Tert-Butanol	0.039	2	6.602
				Hydrogen	0.000	0	0.000
				Methacrolein	0.053	2	8.956
				Oxygen	0.001	0	0.000
				M-acrylate	0.208	3	53.097
							169.255
CRV 103 bottom	2.00	855.11	172.38	Methanol	0.020	2	7.033
				MMethAcryl	0.649	2	223.609
				H20	0.137	0	0.000
				Tert-Butanol	0.014	2	4.654
				Hydrogen	0.000	0	0.000
				Methacrolein	0.030	2	10.412
				Oxygen	0.000	0	0.000
				M-acrylate	0.150	3	77.570
							323.278
Methanol	7.09	737.45	62.30	Methanol	1.000	2	124.607
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.000	3	0.000
							124.607
K100 out	10.00	9.62	206.08	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.028	0	0.000
				Tert-Butanol	0.028	2	11.334
				Hydrogen	0.000	0	0.000
				Methacrolein	0.048	2	19.619
				Oxygen	0.044	0	0.000
				M-acrylate	0.853	3	527.113
							558.067

E101 out	10.00	225.05	206.08	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.028	0	0.000
				Tert-Butanol	0.028	2	11.334
				Hydrogen	0.000	0	0.000
				Methacrolein	0.048	2	19.619
				Oxygen	0.044	0	0.000
				M-acrylate	0.853	3	527.113
							558.067
CRV 101 feed	4.86	10.25	102.95	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	1.000	2	205.897
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.000	3	0.000
							205.897
CRV 102 feed	3.75	3.44	147.39	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.282	0	0.000
				Tert-Butanol	0.119	2	34.991
				Hydrogen	0.000	0	0.000
				Methacrolein	0.324	2	95.393
				Oxygen	0.000	0	0.000
				M-acrylate	0.276	3	121.953
							252.336
CRV 101 bottom			0.00	Methanol		2	
				MMethAcryl		2	
				H20		0	
				Tert-Butanol		2	
				Hydrogen		0	
				Methacrolein		2	
				Oxygen		0	
				M-acrylate		3	
							0.000
T100 top	3.50	707.06	65.14	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.269	2	35.008
				Hydrogen	0.000	0	0.000
				Methacrolein	0.731	2	95.202
				Oxygen	0.000	0	0.000
				M-acrylate	0.001	3	0.117
							130.327

T100 bottom	3.50	883.87	82.25	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.505	2	83.071
				Hydrogen	0.000	0	0.000
				Methacrolein	0.001	2	0.197
				Oxygen	0.000	0	0.000
				M-acrylate	0.494	3	121.843
							205.112
T101 top	3.50	813.50	40.52	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.002	2	0.195
				Oxygen	0.000	0	0.000
				M-acrylate	0.997	3	121.249
							121.443
T101 bottom to WWT	3.50	913.85	41.73	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.995	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.005	3	0.601
							0.601
K100 in	3.50	3.61	206.08	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.028	0	0.000
				Tert-Butanol	0.028	2	11.334
				Hydrogen	0.000	0	0.000
				Methacrolein	0.048	2	19.619
				Oxygen	0.044	0	0.000
				M-acrylate	0.853	3	527.113
							558.067
E102 out	2.00	783.59	85.30	Methanol	0.119	2	20.318
				MMethAcryl	0.471	2	80.282
				H20	0.111	0	0.000
				Tert-Butanol	0.039	2	6.602
				Hydrogen	0.000	0	0.000
				Methacrolein	0.053	2	8.956
				Oxygen	0.001	0	0.000
				M-acrylate	0.208	3	53.097
							169.255

T102 top	5.00	835.26	60.73	Methanol	0.058	2	7.021
				MMethAcryl	0.003	2	0.364
				H20	0.389	0	0.000
				Tert-Butanol	0.038	2	4.664
				Hydrogen	0.000	0	0.000
				Methacrolein	0.086	2	10.410
				Oxygen	0.000	0	0.000
				M-acrylate	0.426	3	77.581
							100.040
T102 bottom	5.00	757.35	111.65	Methanol	0.000	2	0.000
				MMethAcryl	1.000	2	223.246
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.000	3	0.000
							223.246
V	2.00	2.82	10.70	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.001	0	0.000
				Tert-Butanol	0.003	2	0.053
				Hydrogen	0.000	0	0.000
				Methacrolein	0.013	2	0.267
				Oxygen	0.846	0	0.000
				M-acrylate	0.138	3	4.426
							4.747
L	2.00	931.34	195.38	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.030	0	0.000
				Tert-Butanol	0.029	2	11.293
				Hydrogen	0.000	0	0.000
				Methacrolein	0.050	2	19.343
				Oxygen	0.000	0	0.000
				M-acrylate	0.892	3	522.723
							553.358
Average	**20.7825**	**482.6388**					**246.2665**

$$\boldsymbol{TRRI = (20.78 \times 428.64 \times 246.27) \times 10^{-6}}$$
$$\boldsymbol{= 2.47}$$

Figure 4.1: Tertiary Butyl Alcohol (TBA) for MMA Production

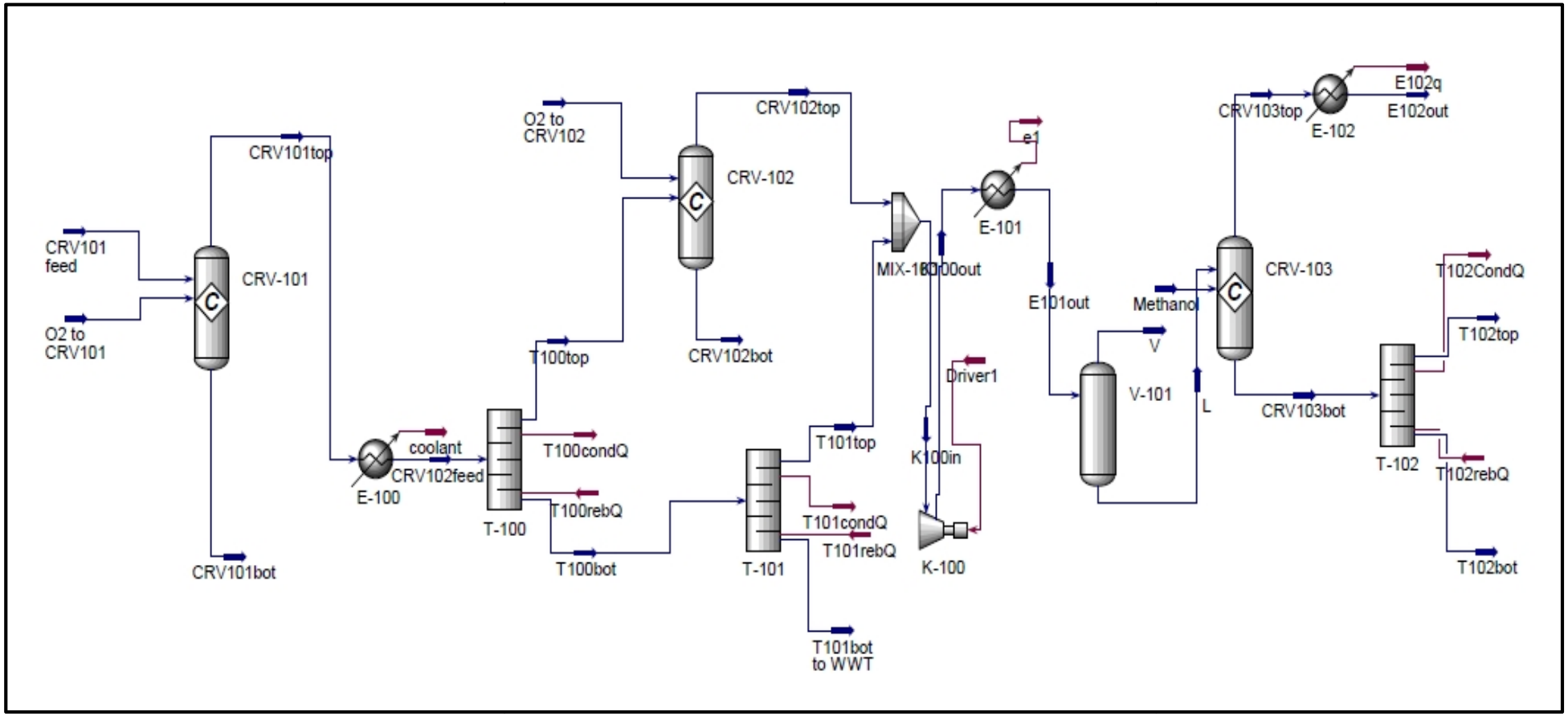


Table 4.2: TRRI calculation for Isobutylene (iC4) based route for MMA production

Stream	Contribution of average data to the TRRI						
	Pressure	Density	Toxicity Level				
	bar	kg/m3	Mass Flow	Component	Mass Fraction	TLV Score	TL
CRV 101 top	**50.00**	**14.18**	244.74	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.164	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.318	2	155.803
				Oxygen	0.000	0	0.000
				M-acrylate	0.391	3	286.937
				i-Butene	0.127	2	62.360
							505.100
CRV 102 top	**3.75**	**3.41**	14.53	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.051	2	1.470
				Oxygen	0.013	0	0.000
				M-acrylate	0.937	3	40.817
				i-Butene	0.000	2	0.000
							42.287
CRV 102 bottom			0.00	Methanol	0.000	2	
				MMethAcryl	0.000	2	
				H20	0.000	0	
				Tert-Butanol	0.000	2	
				Hydrogen	0.000	0	
				Methacrolein	0.051	2	
				Oxygen	0.013	0	
				M-acrylate	0.937	3	
				i-Butene	0.000	2	
							0.000
O2 to CRV 102	**350.00**	**661.02**	6.69	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.253	0	0.000
				M-acrylate	0.747	3	14.994
				i-Butene	0.000	2	0.000
							14.994

O2 to CRV 101	**50.00**	**62.45**	88.89	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	1.000	0	0.000
				M-acrylate	0.000	3	0.000
				i-Butene	0.000	2	0.000
							0.000
CRV 103 top	**7.00**	**7.01**	35.24	Methanol	0.471	2	33.160
				MMethAcryl	0.277	2	19.501
				H20	0.187	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.021	2	1.445
				Oxygen	0.000	0	0.000
				M-acrylate	0.045	3	4.757
				i-Butene	0.000	2	0.000
							58.863
CRV 103 bottom	**7.00**	**813.60**	191.29	Methanol	0.145	2	55.588
				MMethAcryl	0.513	2	196.145
				H20	0.276	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.020	2	7.728
				Oxygen	0.000	0	0.000
				M-acrylate	0.046	3	26.168
				i-Butene	0.000	2	0.000
							285.629
Methanol	**7.09**	**737.45**	62.30	Methanol	1.000	2	124.607
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.000	3	0.000
				i-Butene	0.000	2	0.000
							124.607

K100 out	**7.09**	**6.24**	14.53	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.051	2	1.470
				Oxygen	0.013	0	0.000
				M-acrylate	0.937	3	40.817
				i-Butene	0.000	2	0.000
							42.287
CRV 103 feed	**7.09**	**369.38**	14.53	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.051	2	1.470
				Oxygen	0.013	0	0.000
				M-acrylate	0.937	3	40.817
				i-Butene	0.000	2	0.000
							42.287
CRV 101 feed	**50.00**	**50.50**	155.85	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.000	3	0.000
				i-Butene	1.000	2	311.709
							311.709
CRV 102 feed	**3.75**	**6.11**	7.83	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.939	2	14.714
				Oxygen	0.000	0	0.000
				M-acrylate	0.061	3	1.426
				i-Butene	0.000	2	0.000
							16.140

CRV 101 bottom			0.00	Methanol		2	
				MMethAcryl		2	
				H20		0	
				Tert-Butanol		2	
				Hydrogen		0	
				Methacrolein		2	
				Oxygen		0	
				M-acrylate		3	
				i-Butene		2	
							0.000
VLV 101 out	**3.75**	**302.30**	7.83	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.939	2	14.714
				Oxygen	0.000	0	0.000
				M-acrylate	0.061	3	1.426
				i-Butene	0.000	2	0.000
							16.140
E102 Out	**50.00**	**2719.30**	244.72	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.164	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.318	2	155.792
				Oxygen	0.000	0	0.000
				M-acrylate	0.391	3	286.915
				i-Butene	0.127	2	62.356
							505.063
T100 top	**10.00**	**640.78**	103.84	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.635	2	131.775
				Oxygen	0.000	0	0.000
				M-acrylate	0.065	3	20.343
				i-Butene	0.300	2	62.347
							214.464

T100 bottom	**10.00**	**778.42**	140.90	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.284	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.085	2	24.010
				Oxygen	0.000	0	0.000
				M-acrylate	0.631	3	266.599
				i-Butene	0.000	2	0.000
							290.609
T101 top	**4.00**	**724.80**	7.83	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.939	2	14.714
				Oxygen	0.000	0	0.000
				M-acrylate	0.061	3	1.426
				i-Butene	0.000	2	0.000
							16.140
E103 out	**8.00**	**803.62**	133.07	Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.301	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.035	2	9.288
				Oxygen	0.000	0	0.000
				M-acrylate	0.664	3	265.153
				i-Butene	0.000	2	0.000
							274.442
E104 out	**7.00**	**758.40**	35.24	Methanol	0.471	2	33.160
				MMethAcryl	0.277	2	19.501
				H20	0.187	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.021	2	1.445
				Oxygen	0.000	0	0.000
				M-acrylate	0.045	3	4.757
				i-Butene	0.000	2	0.000
							58.863

T102 top	**7.00**	**671.02**	16.62	Methanol	0.471	2	33.160
				MMethAcryl	0.277	2	19.501
				H20	0.187	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.021	2	1.445
				Oxygen	0.000	0	0.000
				M-acrylate	0.045	3	4.757
				i-Butene	0.000	2	0.000
							58.863
T102 bottom	**7.00**	**823.35**	18.61	Methanol	0.000	2	0.004
				MMethAcryl	0.524	2	19.500
				H20	0.355	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.039	2	1.444
				Oxygen	0.000	0	0.000
				M-acrylate	0.083	3	4.624
				i-Butene	0.000	2	0.000
							25.572
MeOHrcy	**7.00**	**671.02**	16.63	Methanol	0.997	2	33.175
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.003	3	0.135
				i-Butene	0.000	2	0.000
							33.310
T103 top	**7.00**	**818.24**	106.28	Methanol	0.262	2	55.605
				MMethAcryl	0.041	2	8.779
				H20	0.558	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.043	2	9.161
				Oxygen	0.000	0	0.000
				M-acrylate	0.097	3	30.768
				i-Butene	0.000	2	0.000
							104.312

T103 bottom	**7.00**	**730.79**	103.62	Methanol	0.000	2	0.000
				MMethAcryl	0.998	2	206.872
				H20	0.002	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-acrylate	0.000	3	0.000
				i-Butene	0.000	2	0.000
							206.872
T103 feed	**7.00**	**668.72**	209.90	Methanol	0.132	2	55.582
				MMethAcryl	0.514	2	106.462
				H20	0.283	0	0.000
				Tert-Butanol	0.000	2	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.022	2	4.518
				Oxygen	0.000	0	0.000
				M-acrylate	0.049	3	15.201
				i-Butene	0.000	2	0.000
							181.763
Average	**28.23**	**576.76**					**142.930**

$$\boldsymbol{TRRI = (28.23 \times 576.76 \times 142.93) \times 10^{-6}}$$
$$\boldsymbol{= 2.33}$$

Figure 4.2: Isobutylene (i-C4) based route for MMA Production

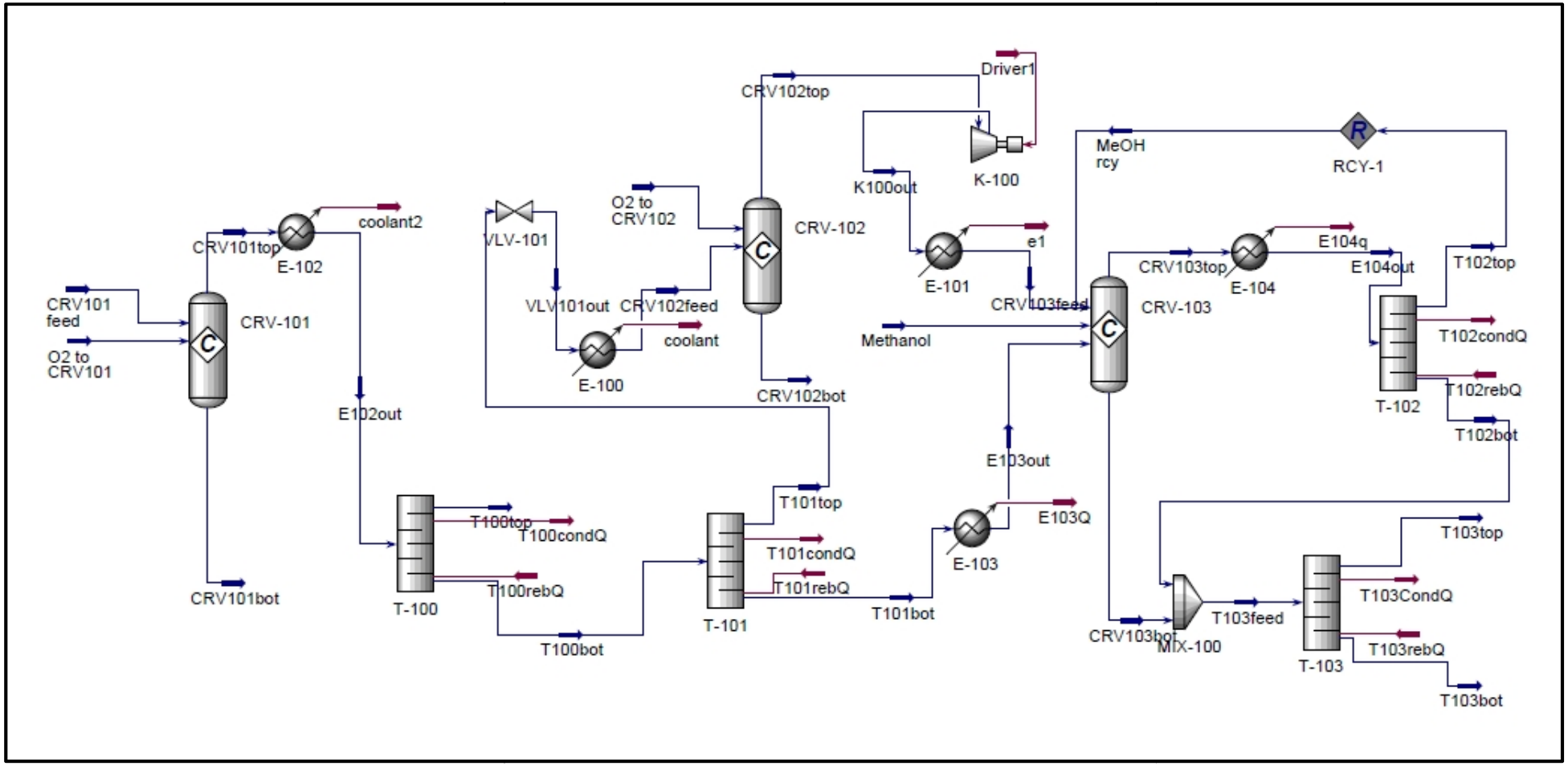


Table 4.3: TRRI calculation for Ethylene via propionaldehyde based route (C2/PA) for MMA Production based route for MMA production

Stream	Contribution of average data to the TRRI						
	Pressure	Density	Toxicity Level				
	bar	kg/m3	Mass Flow	Component	Mass Fraction	TLV Score	TL
mix out	**15.00**	**28.18**	161.34	Ethylene	0.483	2	155.850
				CO	0.482	3	233.436
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.035	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							389.286
ethylene	**15.00**	**459.27**	77.93	Ethylene	1.000	2	155.854
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							155.854
carbon monoxide	**15.00**	**608.16**	77.81	Ethylene	0.000	2	0.000
				CO	1.000	3	233.424
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							233.424

hydrogen	**15.00**	**1.20**	5.60	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	1.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							0.000
CRV100 top	**15.00**	**13.01**	142.00	Ethylene	0.471	2	133.731
				CO	0.475	3	202.386
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.020	3	8.435
				Hydrogen	0.034	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							344.552
CRV100 bottom	**15.00**	**806.26**	19.34	Ethylene	0.037	2	1.423
				CO	0.001	3	0.046
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.962	3	55.837
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							57.307

CRV101 top	**49.65**	**47.73**	19.56	Ethylene	0.003	2	0.102
				CO	0.000	3	0.000
				Formaldehyde	0.033	4	2.559
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.198	0	0.000
				Propanal	0.015	3	0.857
				Hydrogen	0.000	0	0.000
				Methacrolein	0.752	2	29.425
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							32.943
CRV101 bottom	**49.65**	**2433.08**	8.15	Ethylene	0.001	2	0.008
				CO	0.000	3	0.000
				Formaldehyde	0.050	4	1.627
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.184	0	0.000
				Propanal	0.004	3	0.095
				Hydrogen	0.000	0	0.000
				Methacrolein	0.762	2	12.416
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							14.147
CRV102 top	**350.00**	**195.25**	7.12	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.023	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.134	2	1.915
				Oxygen	0.038	0	0.000
				M-Acrylate	0.806	3	17.215
							19.130

CRV102 bottom			0.00	Ethylene		2	
				CO		3	
				Formaldehyde		4	
				Methanol		2	
				MMethAcryl		2	
				H20		0	
				Propanal		3	
				Hydrogen		0	
				Methacrolein		2	
				Oxygen		0	
				M-Acrylate		3	
							0.000
Oxygen	**350.00**	**257.49**	1.33	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	1.000	0	0.000
				M-Acrylate	0.000	3	0.000
							0.000
Formaldehyde	**49.65**	**42.37**	10.01	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	1.000	4	40.034
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							40.034

CRV103 top	**7.09**	**9.76**	2.74	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.080	2	0.438
				MMethAcryl	0.483	2	2.646
				H20	0.129	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.134	2	0.731
				Oxygen	0.097	0	0.000
				M-Acrylate	0.077	3	0.631
							4.446
CRV103 bottom	**7.09**	**787.69**	6.61	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.014	2	0.186
				MMethAcryl	0.704	2	9.309
				H20	0.133	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.089	2	1.176
				Oxygen	0.000	0	0.000
				M-Acrylate	0.059	3	1.176
							11.847
Methanol	**7.09**	**781.25**	2.23	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	1.000	2	4.450
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							4.450

E101 in	**7.09**	**3.60**	7.12	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.023	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.134	2	1.915
				Oxygen	0.038	0	0.000
				M-Acrylate	0.806	3	17.215
							19.130
E101 out	**7.09**	**161.89**	7.12	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.023	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.134	2	1.915
				Oxygen	0.038	0	0.000
				M-Acrylate	0.806	3	17.215
							19.130
E103 out	**15.00**	**753.63**	19.34	Ethylene	0.037	2	1.423
				CO	0.001	3	0.046
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.962	3	55.837
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							57.307

CRV101 feed	**49.65**	**796.13**	17.71	Ethylene	0.003	2	0.106
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.997	3	52.961
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							53.067
CRV102 feed	**354.64**	**365.16**	5.80	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.028	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.972	2	11.275
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							11.275
X100 top	**49.65**	**34.89**	0.44	Ethylene	0.009	2	0.008
				CO	0.000	3	0.000
				Formaldehyde	0.919	4	1.627
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.072	3	0.096
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							1.731

X100 bottom	**49.65**	**2491.55**	7.71	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.195	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.805	2	12.417
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							12.417
T100 top	**43.00**	**705.19**	1.92	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.698	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.302	2	1.159
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							1.159
T100 bottom	**43.00**	**3604.63**	5.79	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.028	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.972	2	11.258
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							11.258

heavy liquid			0.00	Ethylene	0.000	2	
				CO	0.000	3	
				Formaldehyde	0.000	4	
				Methanol	0.000	2	
				MMethAcryl	0.000	2	
				H20	0.028	0	
				Propanal	0.000	3	
				Hydrogen	0.000	0	
				Methacrolein	0.972	2	
				Oxygen	0.000	0	
				M-Acrylate	0.000	3	
							0.000
light liquid	**1.00**	**794.72**	17.71	Ethylene	0.003	2	0.106
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.997	3	52.961
				Hydrogen	0.000	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							53.067
vapour	**1.00**	**1.61**	1.63	Ethylene	0.403	2	1.314
				CO	0.010	3	0.046
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.000	0	0.000
				Propanal	0.587	3	2.872
				Hydrogen	0.001	0	0.000
				Methacrolein	0.000	2	0.000
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							4.233

P101 out	**354.64**	**623.48**	5.79	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Formaldehyde	0.000	4	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H20	0.028	0	0.000
				Propanal	0.000	3	0.000
				Hydrogen	0.000	0	0.000
				Methacrolein	0.972	2	11.258
				Oxygen	0.000	0	0.000
				M-Acrylate	0.000	3	0.000
							11.258
Average	**74.45**	**646.43**					**60.094**

$$\boldsymbol{TRRI = (74.45 \times 646.43 \times 60.094) \times 10^{-6}}$$
$$\boldsymbol{= 2.89}$$

Figure 4.3: Ethylene via propionaldehyde based route (C2/PA) based route for MMA Production

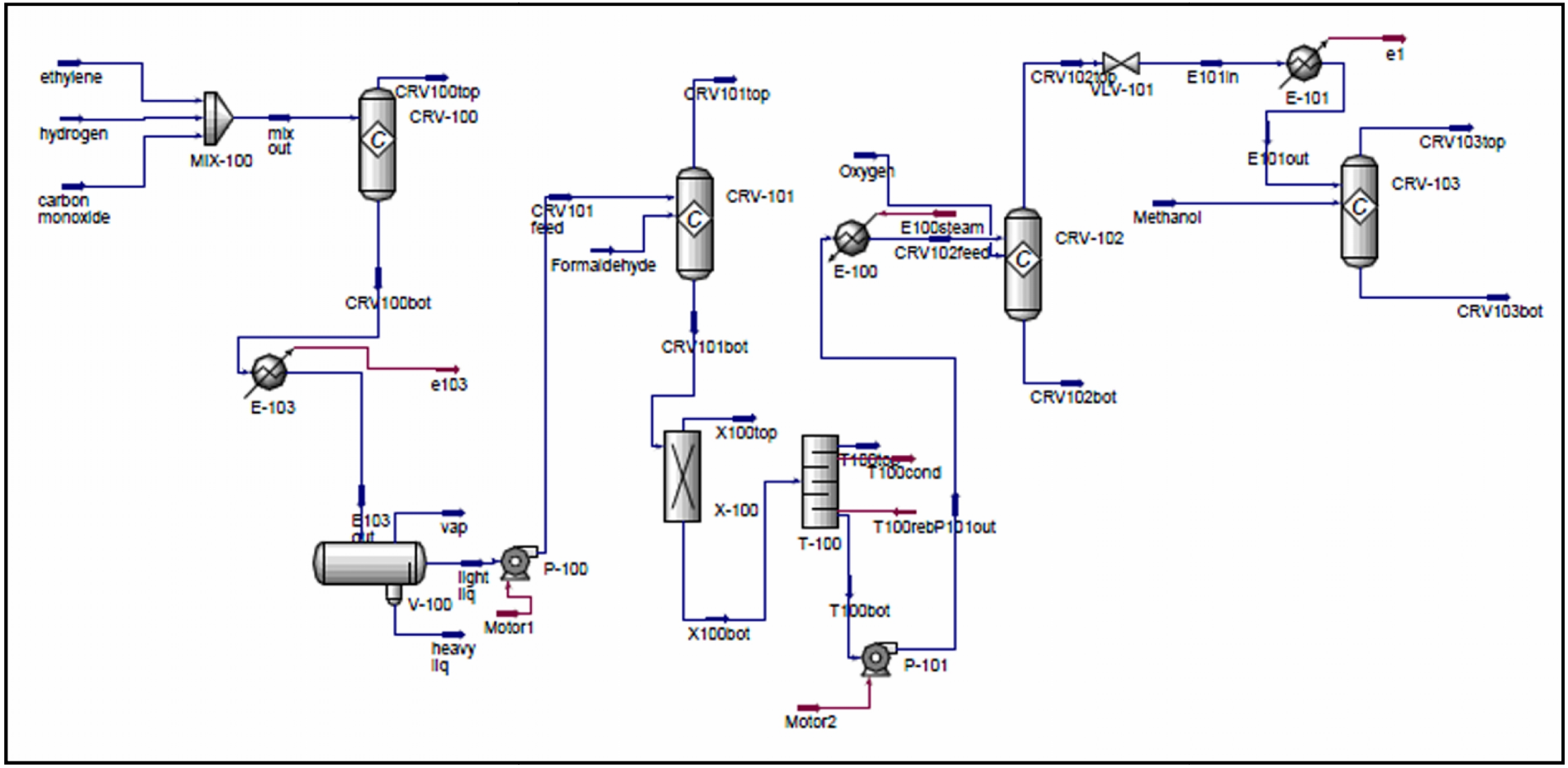


Table 4.4: TRRI calculation for Ethylene via methyl propionate based route (C2/PA) for MMA Production based route for MMA production

Stream	Contribution of average data to the TRRI						
	Pressure	Density	Toxicity Level				
	bar	kg/m3	Mass Flow	Component	Mass Fraction	TLV Score	TL
Ethylene	**101.35**	**91.62**	31.17	Ethylene	1.000	2	62.342
				CO	0.000	3	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							62.342
CO	**20.00**	**565.94**	31.12	Ethylene	0.000	2	0.000
				CO	1.000	3	93.513
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							93.513
MeOH mix	**100.00**	**713.17**	587.43	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	1.000	2	1174.870
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							1174.870
CRV100 top	**50.00**	**37.26**	115.70	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.154	2	35.612
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.846	2	195.784
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							231.395

CRV100 bottom				Ethylene		2	
				CO		3	
				Methanol		2	
				MMethAcryl		2	
				H2O		0	
				M-C3oate		2	
				Methylal		2	
				Oxygen		0	
							0.000
heated CO	**50.00**	**9.26**	31.12	Ethylene	0.000	2	0.000
				CO	1.000	3	93.370
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							93.370
methanol to CRV101	**100.00**	**713.17**	534.03	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	1.000	2	1068.063
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							1068.063
Oxygen	**101.33**	**104.51**	71.11	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	1.000	0	0.000
							0.000
CRV101 top	**100.00**	**78.95**	1199.93	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.636	2	1526.305
				MMethAcryl	0.000	2	0.000
				H2O	0.089	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.276	2	661.639
				Oxygen	0.000	0	0.000
							2187.944

CRV101 bottom	**100.00**	**1908.99**	355.43	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.530	2	376.610
				MMethAcryl	0.000	2	0.000
				H2O	0.151	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.319	2	227.047
				Oxygen	0.000	0	0.000
							603.657
Methanol to CRV100	**100.00**	**713.17**	53.40	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	1.000	2	106.806
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							106.806
E101 out	**100.00**	**1956.60**	1199.93	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.636	2	1526.305
				MMethAcryl	0.000	2	0.000
				H2O	0.089	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.275	2	660.439
				Oxygen	0.000	0	0.000
							2186.744
E102 out	**50.00**	**570.77**	115.70	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.154	2	35.612
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.846	2	195.784
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							231.395
CRV102 bottom	**50.00**	**3765.54**	8791.19	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.070	2	1232.524
				MMethAcryl	0.009	2	160.000
				H2O	0.009	0	0.000
				M-C3oate	0.001	2	17.582
				Methylal	0.911	2	16015.781
				Oxygen	0.000	0	0.000
							17425.888

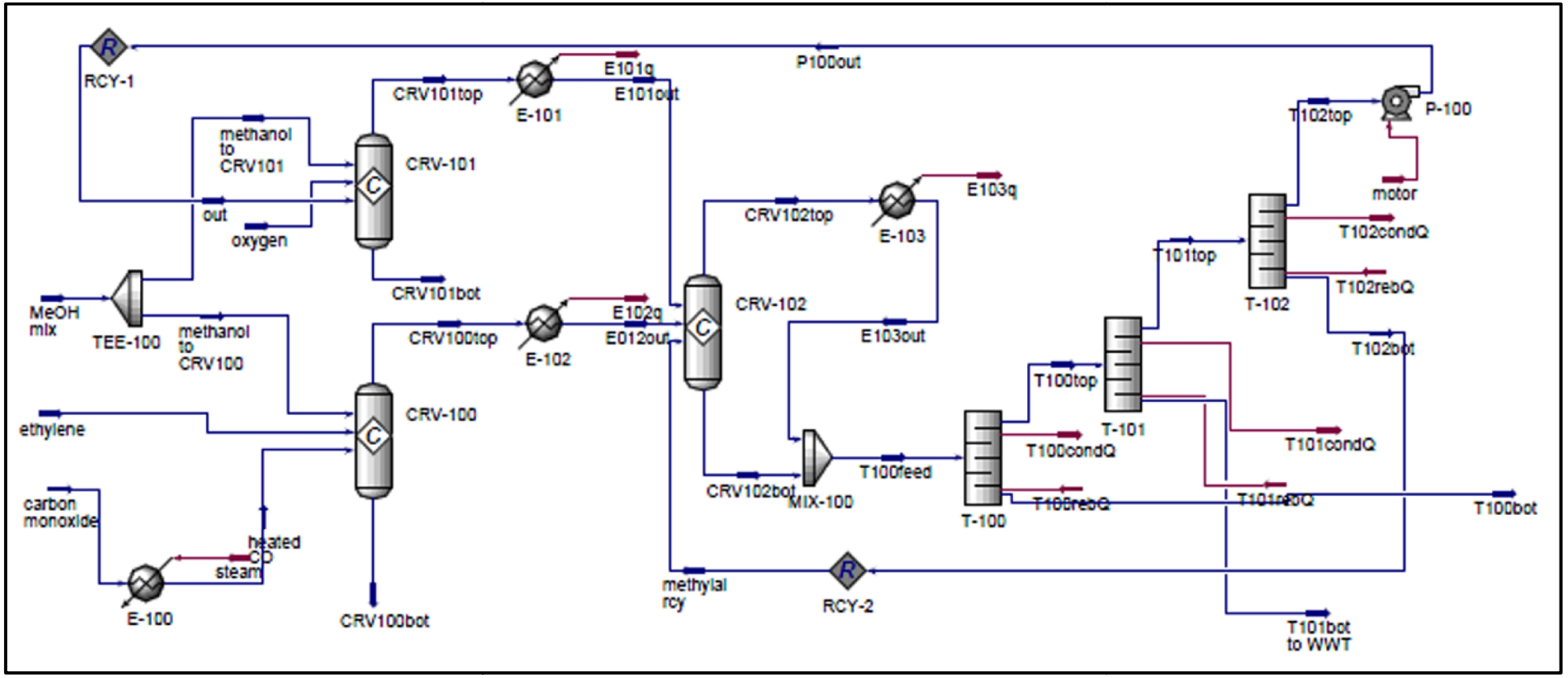
CRV102 top	**50.00**	**83.78**	7093.63	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.077	2	1085.326
				MMethAcryl	0.003	2	35.468
				H2O	0.004	0	0.000
				M-C3oate	0.001	2	7.094
				Methylal	0.917	2	13004.044
				Oxygen	0.000	0	0.000
							14131.931
E103 out	**50.00**	**524.71**	7093.63	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.077	2	1085.326
				MMethAcryl	0.002	2	34.049
				H2O	0.004	0	0.000
				M-C3oate	0.001	2	7.094
				Methylal	0.917	2	13004.044
				Oxygen	0.000	0	0.000
							14130.513
T100 top	**50.00**	**3766.06**	15789.92	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.073	2	2317.961
				MMethAcryl	0.000	2	3.158
				H2O	0.007	0	0.000
				M-C3oate	0.001	2	25.264
				Methylal	0.920	2	29047.143
				Oxygen	0.000	0	0.000
							31393.526
T100 bottom	**50.00**	**5561.26**	94.89	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	1.000	2	189.785
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.000	2	0.000
				Oxygen	0.000	0	0.000
							189.785
T100 feed	**50.00**	**3773.33**	15884.82	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.073	2	2319.183
				MMethAcryl	0.006	2	193.795
				H2O	0.007	0	0.000
				M-C3oate	0.001	2	25.416
				Methylal	0.913	2	29018.382
				Oxygen	0.000	0	0.000
							31556.776

T101 top	**50.00**	**3837.08**	15660.63	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.074	2	2317.773
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.926	2	29003.489
				Oxygen	0.000	0	0.000
							31321.262
T101 bottom to WWT	**50.00**	**740.47**	129.29	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.000	2	0.000
				MMethAcryl	0.018	2	4.655
				H2O	0.824	0	0.000
				M-C3oate	0.095	2	24.669
				Methylal	0.063	2	16.187
				Oxygen	0.000	0	0.000
							45.511
T102 top	**100.00**	**1902.48**	944.99	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.889	2	1679.997
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.111	2	209.976
				Oxygen	0.000	0	0.000
							1889.973
T102 bottom	**100.00**	**4105.15**	14715.64	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.022	2	638.659
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.978	2	28792.630
				Oxygen	0.000	0	0.000
							29431.289
P100 out	**100.00**	**1902.48**	944.99	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.889	2	1679.997
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.111	2	209.976
				Oxygen	0.000	0	0.000
							1889.973

out	**100.00**	**1902.48**	950.21	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.889	2	1689.282
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.111	2	211.137
				Oxygen	0.000	0	0.000
							1900.419
Methylalrcy	**100.00**	**4105.15**	14569.20	Ethylene	0.000	2	0.000
				CO	0.000	3	0.000
				Methanol	0.889	2	25901.126
				MMethAcryl	0.000	2	0.000
				H2O	0.000	0	0.000
				M-C3oate	0.000	2	0.000
				Methylal	0.111	2	3237.276
				Oxygen	0.000	0	0.000
							29138.402
Average	**74.91**	**1737.33**					**8499.414**

$$\boldsymbol{TRRI = (74.91 \times 1737.33 \times 8499.414) \times 10^{-6}}$$
$$\boldsymbol{= 1106.10}$$

Figure 4.4: Ethylene via methyl propionate based route (C2/MP) based route for MMA Production



4.2 Discussion

The Toxic Release Route Index (TRRI) value is an absolute number without references, the applicability of TRRI is extended by adopting the relative ranking of the index to determine the ISL as such.

Table 4.5: Relative Ranking of TRRI for Four MMA Production Routes

Methyl Methacrylate (MMA) Process Route	TRRI	Relative Rank
Ethylene via methyl propionate based route (C2/MP)	1106.10	4
Ethylene via propionaldehyde based route (C2/PA)	2.89	3
Isobutylene based route (i-C4)	2.33	1
Tertiary Butyl Alcohol based route (TBA)	2.47	2

From the table above, the TRRI shows that the i-C4 route is ranked first in term of ISL from the perspective of toxicity. The second safest route from TRRI is the TBA route followed by C2/PA route, while the C2/MP route is ranked the last.

Since TRRI is a new index to quantify the ISL of a process route for toxic release using fundamental process parameters that influence the outcome for toxic release, the most well-known case study referred to by previous inherent safety indices, Methyl Methacrylate Acid (MMA) production has been used as demonstration case. This hypothesis is compared against the previous research findings.

Table 4.6: Ranking of MMA processes by various indices

Methyl Methacrylate Acid (MMA) Process Route	Lawrence - PIIS	Expert Opinion	Heikkila - ISI	Leong & Shariff - PRI	Toxic Release Route Index (TRRI)
Ethylene via methyl propionate based route (C2/MP)	3	3	2	4	1106.10 (4)
Ethylene via propionaldehyde based route (C2/PA)	4	4	3	3	2.89 (3)
Isobutylene based route (i-C4)	2	2	1	2	2.33 (1)
Tertiary Butyl Alcohol based route (TBA)	1	1	1	1	2.47 (2)

The table shows the comparison between TRRI against the published results of the previous indices based on case studies using process routes to produce methyl methacrylate acid (MMA). Process design simulation cases using HYSIS were built based on published data by Lawrence (1996). A comparison of TRRI results with the results of PIIS (Lawrence, 1996), ISI (Heikkila, 1999), and i-Safe (Palaniappan, 2002) which were discussed in Leong and Shariff (2009) together with expert opinion are produced as table.

When analysing the results, all of the method agree that TBA route is the most inherently safe route except for Heikkila. Heikkila's ISI was not able to distinguish the inherent safety level of TBA and i-C4 route. However, it is in agreement with expert opinion that C2/PA route is the most inherently unsafe. The comparison in the table also shows that the PIIS results are in close agreement with expert opinion.

The main reason of the difference in the ranking of indices is related to the difference in their sub indices structure and properties. For example, the PIIS evaluation is based on the reaction steps and it does not consider separation section at all (Rahman et. Al, 2005). Leong and Shariff (2009) also noted similar observation and they mentioned that all the previous indices suffer to some extent from simplification and the lack of sub indices interaction. In the review, they noted for example, that a large inventory of dangerous and harmless chemical affects the level of safety in reality. However, due to the lack of interaction between sub indices, the considered case study attained the same inventory index values, since the inventory ignored the type of content.

Table 4.7: Summary of General Observation of Previous Indices

Indices	Observations
Prototype Index Inherent Safety (PIIS)	• Very step oriented and does not consider separation sections at all • Lacks of inventory evaluation • Very straightforward and fast to use
i-Safe	• Step oriented index and easy to use • Covered reaction hazards • Lack of inventory evaluation and does not consider separation section
Inherent Safety Index (ISI)	• Largest set of sub indices • More factors are covered • Process diagram is needed for the equipment index • Information is not readily available

The results of TRRI for each route and its ranking are given in the most right column in table. Based on TRRI, the i-C4 route is the most inherently safe route followed by TBA. However, we can see that there is only a slight difference between the two TRRI values of thee routes. This may be due to some elements in TRRI are obtained from Heikkila which also cannot distinguish the inherent safely level of TBA ans i-C4 route. Other than that, TRRI produce results that are in good agreement with PRI since TRRI is following the same fundamental as PRI. Both TRRI and PRI have the ability to account for properties of mixture in a route i.e. treat the chemical component as a mixture rather than an individual component for quantifying inherent safety level (ISL).

CHAPTER 5: CONCLUSION & RECOMMENDATION

The application of Inherent Safety (IS) in the process industry is a very attractive proposition and is expected to bring benefits from safety and overall lifecycle cost perspectives. Inherent safety application aims to reduce or eliminates the root causes of hazards by modifying the design of the process plant itself instead of relying on additional engineered safety systems and features which can do fail.

The present work only considers the consequences and risk evaluation for toxic release. In order to provide more comprehensive analysis, the development of consequences model for other hazards to integrate them with TRRI should be proposed in future work.

As a conclusion, Inherent Safety Level quantification remains as one of the important factor in the challenge for inherent safety concept to gain industry acceptance. Few pioneering indices to quantify inherent safety have been proposed in the past. These indices, though simple to use, still have many rooms for improvement in order to represent the process stream condition more accurately. An inherent safety option may not always be the best option. Inherent safety can be costly or not feasible within the project timetable compared to trusted add-ons measures. Rather, the aim of inherent safety is to encourage designers to integrate safety with design and to tackle safety issues at the earliest stage possible.

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